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LCA evaluation and Energy performance of a housing building in different technological scenarios

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Abstract. Reaching nearly Zero Energy Building (nZEB) standards through retrofit can be achieved by adopting controlled procedures and assessment tools. The main issue of operational energy consumption before and after refurbishment should be calculated with reliable predictive models to support investment payback time evaluations. For that purpose, dynamic simulation can reduce the performance gap between simulated and actual performance, however, multiple issues are involved. In the EU Directives, the nZEB framework addresses the operational consumption, which traditionally was the main portion in the building life cycle. However, where nZEB is concerned, the running energy is strongly reduced and embedded energy and disposal assume a higher contribution to the energy life cycle cost. It is worthy to note that LC-ZEBs (Life Cycle Zero Energy Buildings) have been conceptualized more than 10 years ago and the LCA (Life Cycle Assessment) approach is now integrated into the most advanced CVEs (Calculation Virtual Environments) to enable a broader evaluation of building energy during the lifespan. The paper presents LCA scenarios for a housing case study located in Italy and Norway where energy saving is regulated and suitable solutions are strongly connected to materials and energy supply contexts.

1. Introduction

Current energy regulations in EU Countries include energy efficiency and nZEB [1] concepts supporting a standard version of efficiency in buildings and advanced measures also adopted for energy retrofit. Calculation tools are vertically focused on this segment of energy evaluation and the same tools are often able to create, compare and propose virtuous scenarios as well as support the decision process [2]. Their extension to life cycle calculations for building assessment [3] implies the use of connected software, which is in the better cases interoperable with current energy tools [4]. Life cycle assessments rely on archives of materials and embedded energy-related data that can be associated with the imported geometry. Thanks to the simplification offered by interconnected tools, LCA can be introduced in the early stage of design to evaluate different material scenarios encouraging a paradigm shift towards a broader use of LCA.

This paper reports an interoperable procedure for energy assessment in LCA that has been investigated and tested on a residential case study. The building has been located in two European climates, with different regulations and technological scenarios, in Brescia (Italy) and Trondheim (Norway). Italy mainly uses gas as



fuel (52%) in the final energy consumption in the residential sector (59.8% for heating and 65.5% for the DHW) [5], while Norway relies on electricity for both heating (63.1%) and for the DHW production (96.2%) [6]. The goal of this research is to establish whether a high energy performance building, located in two different countries, has a lower environmental impact than a minimum energy performance building, in terms of global warming potential (GWP), as measured in kgCO_{2e} emissions [7]. The comparative assessment has the ambition of including running energy as well as building materials and construction technologies; for this reason, an LCA has been performed following the EN 15978 directive [8].

2. Scientific methodology

The paper proposes a workflow for performing a building LCA to support decision making processes for energy saving measures, materials choice and suitability of technological solutions. The CVEs (Calculation Virtual Environments) interoperable workflow includes IDA-ICE (<https://www.enup.it/ida-ice/>) for the dynamic simulation of the operational phase and OneClick-LCA (<https://www.oneclicklca.com/>) for the LCA assessment; they have been applied to a housing case study located in Brescia (Italy) and Trondheim (Norway). Two sub-models, with different energy efficiency strategies, have been identified for each target country according to the main interventions adopted in the two different technological, energy and social contexts.

2.1. Energy classification for models definition

The energy classification in Italy [9] requires a value of non-renewable primary energy for heating, DHW (domestic hot water) and cooling ($EP_{gl,nren}$) with classes ranging from G to A4, while defining thermal transmittance and HVAC efficiency for the specific climate zone. In Norway the energy classification is based on the primary energy for heating ($EP_{H,nren}$) based on the peak power, plus a standard energy consumption for lighting, equipment, and DHW of 28.9 kWh/m² year; thus the total primary energy is given by the following equation:

$$EP_{gl,nren} = EP_{H,nren} + 28.9 \text{ kWh/m}^2 \text{ year} \quad (1)$$

The local energy regulation proposes two standards: "Minimum requirements" (MR) and "Energy saving measures" (ESM). The former has U values about 0.18-0.22 for the opaque envelope and a leakage at 50 Pa lower than 1.5 while the latter is close to the Passive House standard and has U values reduced by 0.18-0.20 and leakage at 50 Pa lower than 0.6. The energy classification ranges from G to A, where C is based on the MR in the current technical regulation, and A is closer to a passive house [10].

2.2. Models definition

The same case study has been simulated in Italy: three sub-models with the same envelope U-values according to class A3/A4 and different thermal system, with a condensing boiler (CB) and an air to air heat pump (AHP) coupled to photovoltaic and solar thermal systems for the use of renewable energy sources (RES), and a slightly different management:

- Energy class A2, CB (COP 2.1), temperature set point 20-19°C;
- Energy class A3, CB (COP 2.1), temperature set point 19-18°C;
- Energy class A4, AHP and RES, temperature set point 19-18°C;

In Norway, the case study has been simulated with the following performance configurations:

- Minimum requirements MR;
- Energy saving measure ESM.

A sub-model with RES was not created for the Norwegian case as all the electricity coming from the grid is produced with RES. This was the first round of simulations for operational phase comparison.

2.3. LCA evaluation

Following the nomenclature of the directive EN 15978 [8], the LCA analysis includes the product stage (A1-A3) and the operational energy use (B6), water use (B7), maintenance and materials replacement (B1-B5), and deconstruction (C1-C4), while the loads beyond the building life cycle (D) have been accounted for separately. Consistently with the goal of the study, the functional unit is 1 m² of heated area per year, considering a reference service life of 30 years. Calculations have been run with the support of the OneClick LCA software. The materials included in the analysis are those used in foundations, vertical structures and façade, and horizontal structures. By contrast, the material inventory does not include the basin cabinet, shower cabinet, pipes for the heating systems, radiators, cable, pipe for the water distribution, sewers, nails, dowels, steel plates for the connection in the timber frame building or the solar thermal collectors, due to the lack of quantifiable

information. Construction site operation (A5) is neglected for lack of data; in any case, considering the same building technology in Italy and Norway it is sound to consider that these impacts are comparable. In module D exported energy is included among the benefits. For brevity, in the present study GWP only is presented. The carbon footprint (kgCO_2e) is the total amount of greenhouse gases produced throughout the life-cycle of a building. The complexity of the calculation is supported by digital tools that link databases of embodied energy and environmental impact of the materials and systems of the construction with the energy performance of a building in a specific context and related to a local energy mix. Nowadays, a new generation of tools (e.g. One Click, Tally, Open LCA, IES, GBS, etc.) are available, promoting the interoperability processes with energy performance evaluation software to integrate the energy evaluation throughout the different phases (i.e. construction, operational life and demolition/disposal). Therefore, a second round of comparison was performed in terms of emissions due to embodied energy, changing the materials with the high contribution in term of GWP (global warming potential) which means 1) the structure in concrete and 2) the insulation layer in rockwool. For these two materials, widely used in the current construction practice, options for a lower impact have been tested. The following “eco-friendly materials” improvements are thus introduced in models and simulated: a) the concrete improvement is obtained by using 40% of recycled binders; b) the insulation material improvement is obtained using cellulose organic insulation.

Table 1: GWP for the tested construction materials.

Category	Typology	Materials	GWP [$\text{kgCO}_2\text{e}/\text{m}^3$]
Structural elements	standard	C20/25, 0% recycled binders	238.18
	eco-friendly	C20/25, 40% recycled binders	163.45
Insulation layer	standard	rockwool $\lambda = 0.037 \text{ W/mK}$	152.00
	eco-friendly	Cellulose $\lambda = 0.039 \text{ W/mK}$	11.21

Moreover, the use of cellulose required an increased thickness to provide the same insulation performance of the rockwool, this means, in volumetric terms, a higher quantity of material compared to the rockwool solution due to the difference in conductivity and thus insulation potential. Different technological scenarios have been considered as the most used material in Italy is reinforced concrete with masonry walls and timber roof, while, in Norway timber frame houses prevail. The final analysis carried out through Oneclick LCA software is based on the following comparisons reported in Table 1 and focused on the models with the best performances obtained in the first simulation round.

Table 2: Test cases for the LCA evaluation.

Country	Sub-model	Typology	Materials	Heating system
Italy	Sub-model 19°-18°	Standard	0% of recycled binders, rockwool insulation	CB (COP 2.1)
		eco-friendly	40% of recycled binders, cellulose insulation	
	Sub-model PV	Standard	0% of recycled binders, rockwool insulation	AHP+RES
		eco-friendly	40% of recycled binders, cellulose insulation	
Norway	MR	standard	0% of recycled binders, rockwool insulation	Electric radiator system
		eco-friendly	40% of recycled binders, cellulose insulation	
	ESM	standard	0% of recycled binders, rockwool insulation	
		eco-friendly	40% of recycled binders, cellulose insulation	

3. Case study

The test case is a two-floor housing building with a heated area equal to 160.5 m^2 , heated volume of 526.9 m^3 organized in 9 thermal zones. The Italian case has a structure in reinforced concrete (RC), while the Norwegian case has a timber structure. For the Italian case the simulation used the U-values suggested by the local CasaClima Protocol [12] (ranging from 0.16 to $0.18 \text{ W/m}^2\text{K}$ for opaque enclosures), by keeping constant the efficiency value of heating and domestic hot water system (condensing gas boiler COP 2.1). For Norway two distinct methodologies, as introduced in section 2.2, have been modeled, namely MR and ESM, with the latter characterized by more conservative U-values: this implies an increase in the insulating material used which can vary from 20% up to 34%. For the heating system the efficiency has been kept unchanged (COP 1) using electricity as main energy source.

3.1. Climate and location

Brescia (Italy) and Trondheim (Norway) have been used as location for the energy calculation; Brescia is in the Italian climate zone E (2410 Degree Days). The regulation in Norway defines 7 climate zones, however as

76% of dwellings are located in areas with a climate comparable to or milder than the Oslo climate [11] the official weather file adopted for the energy calculation is the one related to Oslo.

3.2. Building modelling and first round simulation

The energy performance in the running phase (B6 in LCA) has been dynamically simulated with IDA-ICE software. The building has been defined in detail as a timber structure (Timber Frame GL28h C/C 600 mm, green line; Cross Laminated Timber CLT CL28h for the staircase, blue line in Figure 1); assessed were envelope component and performance, thermal bridges and technological connections. The system was modelled with a 400-litre hot water tank made of stainless steel, with a triple coil, combi-boiler designed for solar thermal collectors (providing the 60% of the DHW) and heat pumps, suitable for a 4-person household set in the system.

For the Italian models the following results were achieved:

- Energy class A2 $EP_{gl,nren} = 51 \text{ kWh/m}^2\text{y}$, CB (COP 2.1), temperature set point 20-19°C;
- Energy class A3 $EP_{gl,nren} = 46 \text{ kWh/m}^2\text{y}$, CB (COP 2.1), temperature set point 19-18°C;
- Energy class A4 $EP_{gl,nren} = 31 \text{ kWh/m}^2\text{y}$, AHP and RES, temperature set point 19-18°C;

As expected, the use of self-produced renewable energy sources improves the energy class of the building by reducing the global classification indicator $EP_{gl,nren}$. In the first two Italian models it was observed that changing only the set point temperature by one degree, there is an improvement of 12% in terms of energy performance. In the Norwegian case, the energy performance simulation gave the following results: with the increase of insulation of 34% in ESM a final consumption reduction of 25% can be reached:

- Minimum requirements MR, energy class B $EP_{gl,nren} = 91 \text{ kWh/m}^2\text{y}$;
- Energy saving measure ESM energy class A $EP_{gl,nren} = 69 \text{ kWh/m}^2\text{y}$.

4. Results

The KPI used for the model comparison included the environmental impact, in terms of GWP (kgCO₂e), considering the phases A1-A3 (Production phase), B6 (Operational energy use) and D (Benefit and loads beyond the system boundary) parts of the LCA procedure. For the running phase, the primary energy $EP_{gl,nren}$ (kWh/m² year) and the energy class have been evaluated. The simulation model imported the data of the material inventory in the LCA assessment tool and the embodied carbon benchmark in 30 years was calculated, demonstrating the effectiveness of the proposed measures and materials choices in the different territorial, energy and technological scenarios. The results have shown that it is not always enough to have a high energy performance during the operational life of a building to achieve a lower environmental impact, at least in terms of GWP, with respect to a less efficient building, in terms of energy demand. In fact, in some cases, a more efficient building can even have a higher LCA impact of about 12%. The Italian results showed that the advantage is obtained when the use of PV is combined with eco-friendly materials because the low contribution associated to the material stage A1-A3 and the exported energy are able to reduce by 87.1% the total carbon dioxide emission, moving from 31 kgCO₂e/m²y to 4 kg CO₂e/m²y and achieving the result of a LC-ZEB. Norwegian models, MR and ESM, are based on improving the building envelope resistance through increased insulation thickness. The former model has a total insulation volume equal to 84 m³ versus 127 m³ of the latter that corresponds to an increase of 34%. Moreover, in the LCA evaluation phase D “next production system” recovery-recycling-reuse-exported energy/potential has a crucial role in the total carbon footprint at the end of life of the building (Figure 1 and 2).

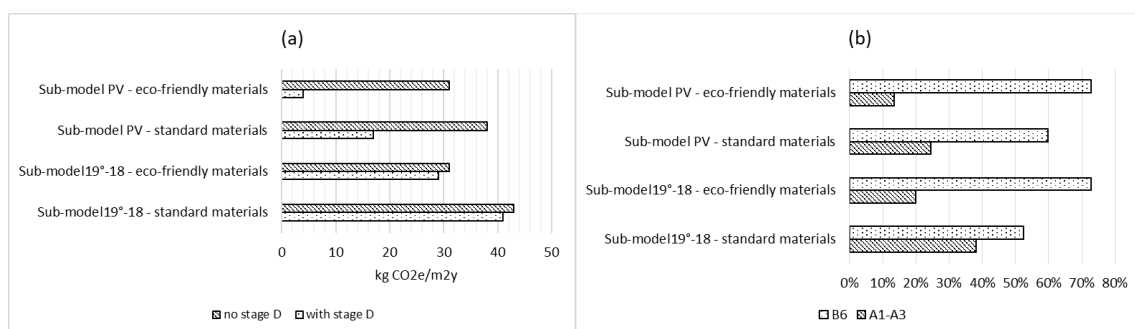


Figure 1: Case study building simulated in Italy: (a) GWP per functional unit with and without the loads of module D; (b) percentage contribution of the construction stage (A1-A3) and the operational energy (B6) to the total GWP

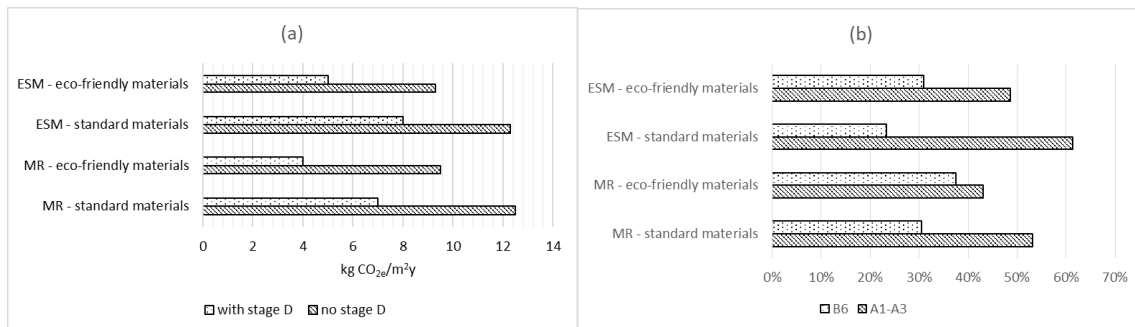


Figure 2: Case study building simulated in Norway: (a) GWP per functional unit with and without the loads of module D; (b) percentage contribution of the construction stage (A1-A3) and the operational energy (B6) to the total GWP

The results showed that the MR that corresponds to an energy class B has a lower environmental impact compared to an energy class A, ESM. The main reason is due to the super insulation and the contribution of the materials as the energy supplied for heating comes from RES. In a recent paper [13] a similar approach, but including a far larger number of parameters, has been applied to the Swiss building stock with the aim of supporting future policies aimed at improving the sustainability of this sector.

5. Discussion and conclusions

This research has documented the LCA (Life Cycle Assessment) evaluation of an efficient Single Family House over a reference service life of 30 years, used as case study. The environmental impacts in terms of total specific carbon footprint (kg CO_{2e}/m²y) have been assessed by comparing different configurations, hypothesis and input data, and geographical localization: Trondheim (Norway) and Brescia (Italy). A similar approach had been used for an in-depth analysis of the Swiss building stock, highlighting how difficult will be reaching 2050 target [13]. Indeed, the present results demonstrated that a high energy performance of a building during the operational life it is not always a guarantee of lower environmental impact in the life cycle perspective, in terms of global warming potential (GWP), when compared to a less efficient building, in terms of energy demand with higher impact of 12%. This result seems to contradict the mainstream approach and it depends on different factors that need be carefully considered. Indeed, the context of intervention in terms of an energy and technical scenario has to include: 1) the country in which the building is located, 2) whether it produces electricity through the use of renewable energies or with traditional sources 3) the typology of the materials used (from non-renewable resource or eco-friendly) and 4) the energy mix used for the heating systems and for the electrical needs. The Italian case study simulations have shown that the use of PV systems, associated with the use of ecological construction materials, drastically reduces the carbon footprint. The advantage is about 77% compared to the use of standard materials, even if the emissions in the initial stage of the life of the building (embodied carbon benchmark) are 40% higher with respect to the models that do not include PV systems (e.g. sub-model19°-18° from 298 kgCO_{2e}/m² to 495 kgCO_{2e}/m²). The main cause is associated to the photovoltaic panels' production carbon footprint (9.2 tonsCO_{2e}). Therefore, referring to this specific case and focusing on the total carbon dioxide equivalent emissions, it is possible to observe that there is an improvement of 87% (from 31 kgCO_{2e}/m²y to 4 kgCO_{2e}/m²y) moving close to Life Cycle Zero Energy Buildings (LC-ZEBs) with the use of renewable energies. This is mainly due to the high global warming potential of electricity in Italy (around 0.50 kg CO_{2e}/kWh); therefore, the energy produced by PV system is able to compensate the CO_{2e} emissions of the building during the entire life cycle. This result can only be achieved when a complete sustainable evaluation is performed embracing the NZEB approach and beyond, which effectively happens when the PVs are associated with eco-friendly materials. When traditional building materials are used, the exported electricity contribution only affects 55% of the total emissions (it goes from 38 kgCO_{2e}/m²y to 17 kgCO_{2e}/m²y). When the photovoltaic system is not included (model19°-18°), it has been shown that the use of ecological materials can reduce the GWP of 28% (from 43 kgCO_{2e}/m²y to 31 kgCO_{2e}/m²y), but, despite also considering the possible recycling of the materials, the global warming potential is still quite high. Therefore, the use of photovoltaic panels and the high energy class A4 (31 kWh/m²y), associated with ecological materials, is demonstrated to be the better solution considering the whole life cycle, and a LC-ZEB [14] concept is achieved. The Norwegian models' simulations have shown contrasting results with respect to the Italian cases. In fact, the increase of 34% of the amount of insulation material, both mineral (rockwool) and eco-friendly (cellulose), required to meet the Minimum Requirements and Energy Saving Measures targets, is

counter-productive with respect to the GWP. This is closely linked to the very low emission factor for the electricity production in Norway (only 0.0234 kgCO_{2e}/kWh). Consequently, the contribution of stages A1-A3 (materials production phase) has a greater impact on the carbon footprint with respect to B6 (operational energy use): an increase in GWP from 43% with eco-friendly materials (MR) to 61.4% with standard ones (ESM) in A1-A3 versus a decrease from 37.5% (MR) to 23.4% (ESM) in B6. Hence, it is possible to conclude that, for the Norwegian models, the building with energy class A (69 kWh/m²y), has a greater environmental impact of about 20% than a building with energy class B (91 kWh/m²y) equipped with eco-friendly materials. This result is achieved with the application of eco-friendly materials also to an ESM model while with standard materials the difference is 50%. A possible future implementation could be to include the economic criterion through an evaluation of the Life Cycle Cost (LCC) for both countries and compare total carbon dioxide equivalent emissions and investment trying to find a balance between the environmental and economic criteria.

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